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ROUTING IN PACKET SWITCHING BROADCAST RADIO NETWORKS*

by

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ABSTRACT

Packet switching broadcast radio networks are receiving considerable attention as a feasible solution for applications involving fast network deployment requirements, inaccessible physical environments, and mobile communication devices. Such networks also offer economic alternatives to traditional multiplexing schemes for local distribution.

Most of the published papers relating to packet switching broadcast radio networks address the case in which all communication devices are within an effective transmission range of the destination receiver, thus forming a single hop network in which no packet routing is involved. In this paper we address multihop networks. The problems encountered in packet transportation are identified and strategies to resolve these are proposed.

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1. INTRODUCTION

Consider a set of resources (e.g. terminals, computers, human resources) that wish to communicate (i.e. exchange messages). We define the medium via which messages are transported as a communication network. In order to use the network, the resources need a proper interface or connection to the network. Similarly, networks which are not homogeneous (i.e. differ in hardware and/or in the set of rules used for messages transportation) need interfaces or gateways if messages are to be transported between them. The notions of gateway, interface, and connections are synonymous as far as their functional need is concerned. We will use the notion interface mainly in the context of a "hardware connection", gateway in the context of a "software connection" between non-homogeneous networks, and connection in a general context of any type of association.

Network tasks related to packet transportation can be classified as follows:

a. Orgination and destination functions.

b. Relay functions.

c. Management and control functions.

d. Gateway functions.

The gateway functions are needed only when one considers message transportation between non-homogeneous networks (i.e. when the origination and destination resources do not "reside" in the same network).

We consider store and forward packet switching networks in contrast to circuit switching and store and forward message switching networks [Miyahara, 1975]. Network elements are communication nodes and communication channels. The network is a packet switching broadcast network as distinguished from a point-to-point packet switching network, such as the ARPANET. Furthermore, it is a radio network as distinguished from a hardwired cable network. The distinguishing characteristics of the network we consider are:

1. A communication channel in a point-to-point packet switching network is associated with two nodes, say channel (i,j) between nodes i and j. This implies that when node i wishes to send a packet to node j, it transmits the packet on channel (i,j) without the need to specfically address the packet (e.g. via an address field in the packet header) to node j. The notion of a communication channel in a radio network, on the other hand, cannot be associated with two nodes. A node in a radio network broadcasts the packet (we assume ommidirectional antennas) which may be received by a set of nodes (in fact, all nodes within an effective transmission range from the node that emitted the packet). If node i wishes to send a packet to node j (only), it needs to specify in the packer header: "this packet is addressed to node j, all other nodes should discard the packet". This also implies that when node j receives a packet with error, it does not know that the packet was addressed to it ; and consequently cannot request a retransmission of that packet.

2. In a point-to-point network, channel (i,j) is dedicated to nodes i and j; thus, if node i has several packets to be sent to node j, it can queue the packets and use any queueing discipline to transmit them. On the other hand, in the broadcast radio network we consider, the channel is shared by all network nodes. We cannot dedicate the channel to a pair of nodes; we can divide the time into non overlapping intervals, assign to each node an interval for transmission and request each node to receive whenever it does not transmit. Numerous studies, e.g. [Abramson,1970,1973; Kleinrock; 1973; Kleinrock,1975; Roberts 1973; Gitman, 1975], have shown that this "fixed assignment" of the channel capacity is wasteful for many types of applications of radio networks. We shall therefore assume that nodes use a "random transmission scheme "(see above references) which results in a dynamic sharing of the channel capacity without centralized control. The particular scheme used is of no sigificance to the issues addressed inhere. The random transmission scheme, however, implies that, unlike in point-to-point networks, a radio node can simultaneously receive several packets (on the same channel), all of which may be received in error. This, in turn, implies that the probability of receiving a packet with error is much greater than on a point-to-point channel, and that this probability varies as a function of the traffic level in the network, the spatial distribution of the traffic sources, and the spatial distribution of nodes (assuming a fixed effective transmission range).

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The characteristics discussed above, make packet radio networks particularly suitable for applications in which:

a. Resources (e.g. terminals, computers) are mobile, so that a broadcast mode is necessary.

b. Resources are located in remote or hostile locations where hardwire connections are uneconomical or not feasible.

c. The traffic characteristics of resources is of a bursty nature; that is, there is a high ratio of peak bandwidth to average bandwidth requirements.

Specific packet radio networks in the stage of design or in current use were discussed in [NCC,1975].

We say that a network is a "single hop" network if no relay functions are needed at its nodes. Most of the analyses of radio networks address single hop networks (e.g. [Abramson,1973; Kleinrock, 1973]), or intentionally avoid the issue of packet routing by proper assumptions [Gitman,1975]. The issue of packet routing in radio networks was first addressed in [NAC,1973,1974; Frank,1975; Kahn, 1975]. The analysis of multi-hop packet radio networks is extremely difficult and one has to resort to simulation [NAC,1974], or analyse very simple models for studying some properties of such networks. Without efficient routing and flow control in large scale radio networks:

1. A packet may endlessly circulate among nodes.

2. Many copies of a packet will be generated; and

3. If we assume that the destination node is on another network, then many copies of a packet, and/or different copies of one message, will arrive at different gateway nodes and be introduced into other networks.

Idealized results of packet proliteration in radio networks can be observed from the analyses of simplified combinatorial models [NAC,1973; Tainiter,1973]. In these ideal models the nodes are located at corner points of an infinite square grid and time is divided into unit intervals, each interval slotted into segments. A packet emitted by a node can be received only by its four nearest neighbors. If a packet is correctly received by a node, it is retransmitted within the next unit interval of time at a random time slot within the interval. Suppose now that a single packet is emitted from the node at the origin and that the transmission plus the propagation time falls within one unit interval of time. Then after n intervals of time:

(i) the number of nodes which receive the packet for the first time, B(n), is:

$$B(n) = 4n,\ n \geq 1; B(0) = 1$$

(ii) the number of nodes through which the packet transited is:

$$A(n) = \sum_{j=0}^{n} B(j) = 2n^2 + 2n + 1,\ n \geq 0$$

(iii) if we assume that a node can receive and relay a large number of packets within the same time interval, the number of copies of the same packet received by a node at coordinates (d,j) after d + 2k units of time is:

$$N_j^d\ (d + 2K) = \binom{d}{k}\binom{d + 2k}{k + j}\binom{d}{k}^{2k} \xrightarrow{\text{for large } k} 2^{4k}$$

where d is the number of units of time that the packet requires to arrive from the origin to the node, and j is the horizontal number of units.

The above paragraphs demonstrate that a broadcast radio network can easily be saturated and cease to fulfill its function. It also implies that the routing and flow control stratefies used for packet transportation are of outmost importance in the efficient network operation.

The network model we assume is characterized by a large number of nodes which use a random transmission scheme and share a single channel using omnidirectional antennas. Two types of nodes are assumed. A node with origination, destination, and relay functions, which we call a Repeater; and a node with additional capabilities such as gateway, global control, global initialization, accounting, and directory functions; we call the latter a Station. If one assumes a large geographical area which needs to be "covered" with a communication network for serving mobile terminals; one would recognize that not all nodes need to have all the functions (economy consideration). Repeaters which have limited capabilities are provided for area coverage. Stations are provided on the basis of network capacity requirements through the gateways, and for reliability purposes. Throughout the paper we avoid discussing terminals, users, or any other resources that the network serves. These sources are not an integral part of the network by our definition and

do not directly affect the problems discussed inhere. It is assumed that the rules of packet transportation in the network are transparent to terminals. Terminals will contain special communication protocols which will enable them to attach themself temporarily or permanently to a network node and be served by it [NAC,1974].

The problems addressed are: flow control functions related to packet transportation, the rules for packet transportation (routing strategies), and the network architecture implied by the routing. The objectives of packet transportation are:

1. Reliability: insuring that a packet launched into an arbitrary point in the network will reach its destination with high probability.

2. Efficiency: to be able to deliver a large number of messages with a relatively small time delay.

The above objectives are rather qualitative statements. The reason being that it is extremely difficult to evaluate by analysis the algorithms presented in the paper. Our evaluation is in terms of general properties which can be deducted from the theoretical presentation of the algorithms. Furthermore, the probability that a packet will reach its destination ignores the task of end-to-end communication protocols which ideally will insure packet delivery via the mechanism of end-to-end retransmission. In general, given two routing algorithms A and B, we say that A is more efficient than B if it uses less network resources (channel and nodes capacities per packet) than B does. For simulation experiments see [Frank,1975].

We propose three routing algorithms for broadcast radio networks. The Broadcast routing algorithm which satisfies objective (1) but fails to satisfy objective (2); and two algorithms which satisfy both objectives for different traffic patterns. The broadcast algorithm may be needed in an operational network as a backup algorithm and/or for initialization of nodes for using the efficient algorithm under general deployment assumptions, possibly with mobile network nodes.

2. BROADCAST ROUTING ALGORITHM

Given a packet and its destination, a routing algorithm determines the best node (in some sense) to which to send the packet. While in point-to-point packet switching networks, every correctly received packet is accepted for switching and the routing algorithm then determines the outgoing line; in radio networks there is almost no decision to make in determining the next node, the decision made by the routing algorithm is whether to accept the packet for switching. This is a property of our radio network model since many repeaters may correctly receive a packet and the main task becomes to eliminate the "bad" paths rather than to find a "good" one.

The broadcast routing algorithm is merely a flow control procedure which prevents looping and cycling of packets in the network. The following mechanisms are used:

1. A hop-by-hop acknowledgement to guarantee that the packet was accepted by the next repeater.

2. A (maximum) handover number (carried in the packet), which is decremented by a repeater which accepts the packet for switching, and guarantees that the packet will traverse no more than the maximum number of hops assigned.

3. A variable transmission power mechanism which enables to increase the power as a function of the number of transmissions without acknowledgement. The increase in power increases the number of potential receivers.

4. Parameters which control the random transmission scheme (e.g. time interval for rescheduling unacknowledged packets, maximum number of transmissions per packet).

5. A time parameter, FORGET, which is the maximum interval of time during which a packet previously switched by a repeater will not be accepted for switching.

We purposely do not outline a strict routing algorithm. The reader may conceive of several algorithm which utilize items (1) through (5) or a variation of these. Items (1) through (4) are controls which are recommended for all routing algorithms in radio networks. These, however, do not prevent looping and cycling of packets. The particular mechanism which defines the boradcast routing algorithm is item(5).

It is assumed that every packet has a unique identifier and that a repeater has storage for a certain number, say L, of unique identifiers. When a packet receives an acknowledgement or is discarded after exceeding the maximum number of transmissions, its identifier and the time are recorded by the repeater. When a new packet is received, its identifier is compared with identifiers stored and with identifiers of packets waiting for transmission. If a match occurs the packet is not accepted for switching. Thus, when the repeater has storage it accepts a packet for switching if: (i) it did not switch the same packet for at least FORGET seconds, or (ii) it switched L other packets after the arriving packet.

2.1 Properties

1. The algorithm is non-directional. There is no addressing along the path; the destination node recognizes that the packet is for it by comparing the destintion ID against its own ID.

2. If L and FORGET are large, the packet will not be switched by a node more than once.

3. The advantage of this algorithm is its simplicity and reliability;repeaters need not know any information related to network connectivity or the location of the destination node. Furthermore, if the origination and destination nodes are connected, and the maximum handover number assigned to a packet is large compared to the shortest path to the destination, there is a high probability that the packet will reach its destination.

4. The algorithm is inefficient as far as network utilization or maximum throughput are concerned,because, in general, a large number of duplicate packets will be generated. Moreover, when a packet orginiates at the radio network and is destined for another network it is probable that copies of the packet will be introduced into other networks by several gateway nodes (stations), unless communication betweem stations takes place to prevent it.

2.2 Discussion

Among the features which take advantage of the radio network and are not possible in point-to-point (PTP) networks are the transmission power control and a special form of hop-by-hop acknowledgment (HBH ack).

The transmission power control enables to increase network connectivity and bypass failed nodes, thus increaseing network reliability. The HBH ack cannot be directional since the receiving node does not know the ID of the transmitting node. However, there is no need to transmit an acknowledgement packet at all; when the receiving node transmits the packet to the "next" node,the packet can also be received by the node which sent the packet to it; the latter recongnizes that it is an ack by comparing the identifier of the packet received and its handover number against those of packets waiting for retransmission*. In fact, this is more efficient than an specific acknowledgement since a single packet transmission can acknowledge several nodes.

The broadcast routing algorithm has the feature of flooding the network (or a subset of it). This feature can be utilized for mapping the network connectivity by stations for the purpose of assigning routing information to repeaters, and thus obtain more efficient routing. It can also be used when a packet must visit every repeater; for example, when a station needs to change parameters in all repeaters. As for permanent use, it is applicable to networks whose nodes are mobile such that updating routing information based on connectivity becomes infeasible.

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* This form of HBH ack assumes that if node i can receive from from node j, node j can also receive from node i. We assume that every node has at least one such link, otherwise it is considered not connected.

Finally we note that a flooding routing algorithm for PTP networks was suggested in [Boehm,1966]. However, it is easy to verify that the broadcast routing for radio networks described here is much more economical, in terms of storage and processing at nodes, since it takes advantage of network properties. The performance comparison is further enhanced in favor of radio networks when one considers HBH acks.

3. HIERARCHICAL ROUTING ALGORITHM

The main factor which contributes to the inefficiency of the broadcast routing algorithm is its non-directionality property. We attempt to overcome this limitation in the algorithms of this and the next sections.

The assumption that guided the development of the hierarchical routing algorithm is that the radio network will be used for local collection and distribution of traffic. This implies that the traffic pattern in the network is from repeaters to stations(gateways) and from station to repeaters. If there is a traffic requirement from a repeater to another repeater in the network, its routing towards the destination will be via a station. Among other virtues, this method has the advantage of centralized control.

The essence of the techniques is to assign to repeaters routing information, during an initialization procedure, and utilize this information for routing. We refer to the information assigned to a repeater by a station as "hierarchical label", or "label". The set of labels assigned to the repeater network by a single station forms a hierarchical structure of repeaters, or a tree structure rotted at the station. Labels assigned to repeaters may need to be changed during network operation when changes in network topology occur.

The routing strategy performs shorest path (minimum hop) routing from repeaters to stations and from stations to repeaters, and prevents, wherever possible, duplicate copies of a packet from being generated and/or circulated in the network. However, the routing procedure includes sufficient flexibility so that when the first choice shortest path cannot be used, the packet departs from this path and uses a shortest path from its new location.

3.1 The Hierarchical Label

We first discuss the case of a single station. The shortest path routing is obtained by labeling the repeaters to form, functionally, a hierarcical structure as shown in Figure 1. Each label includes the following information: (i) a specific address of the repeater for routing purposes, (ii) the minimum number of hops to the station, and (iii) the specific address of all repeaters on a shortest path to the station, and particularly, the address of the repeater to which a packet has to be transmitted when destined to the station.

A label is composed of H fields. A repeater, say R, at a distance of j-1 hops to the station, has a unique label in which the first j fields contain nonzero integers and the remaining H-j fields are zero; we say that R is at level j of the hierarchy. The repeater to which R addresses its packets when routing towards the station is called the "home" of R. The labels of a set of repeaters at level j, which have the same home repeater, differ only in the entry in field j. Thus, the label of the station has a nonzero entry in the first field and a zero in all other fields; the labels of repeaters at a distance of one hop to that station have the stations' entry in the first field, nonzero unique entires in the second field, and zero in all other fields, etc. Figure 1 shows an example of a labeled set of repeaters which form a tree network for routing purposes.

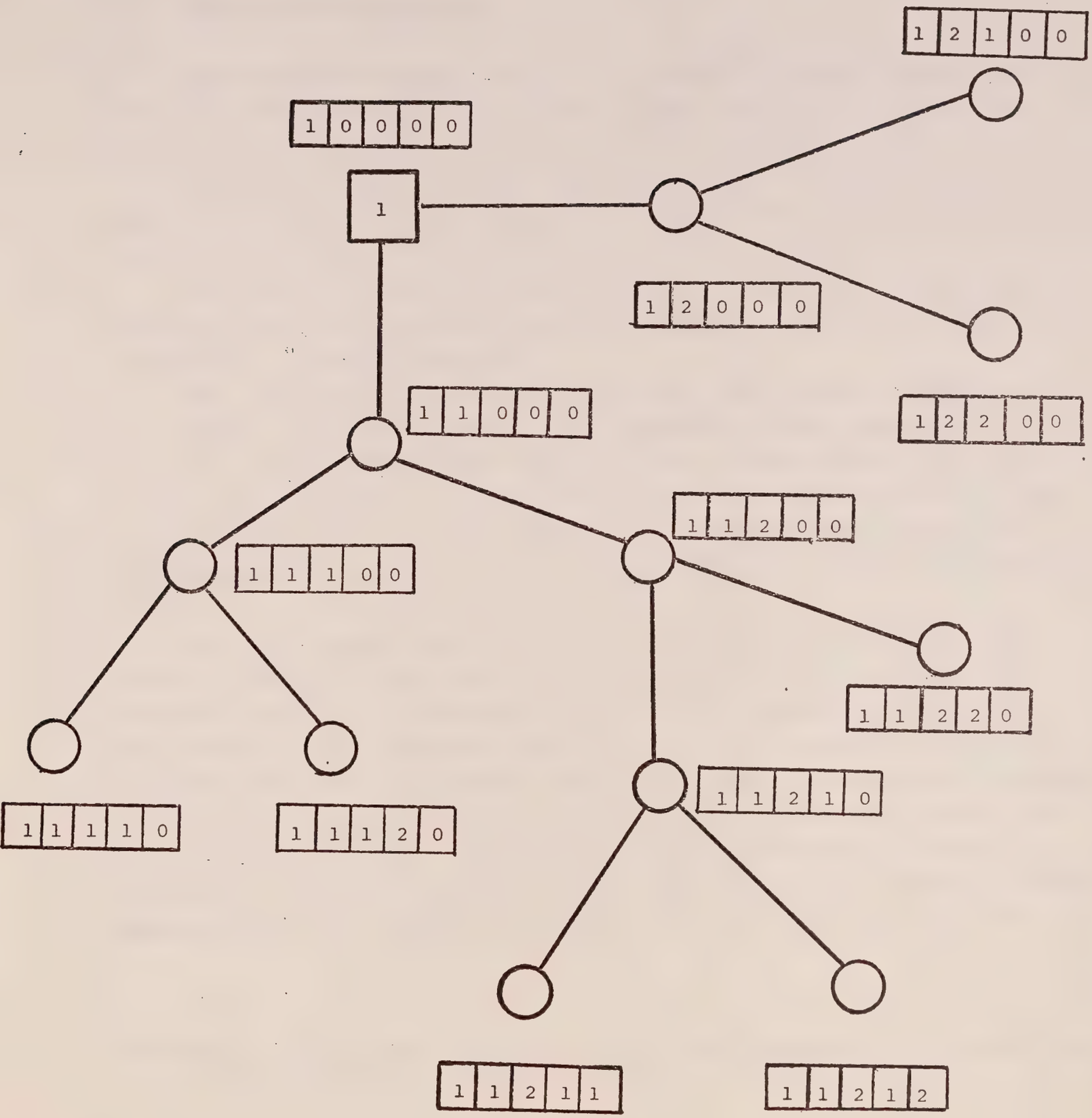

FIGURE 1: THE HIERARCHICAL LABELS OF REPEATERS AND STATION, AND THE TREE STRUCTURE FORMED.

3.2 The Routing Algorithm

Unlike point-to-point routing in which the packet carries the ID of the destination, in the hierarchical routing algorithm the packet carries the path, in the form of the repeater label.

The complete path between the station and a repeater is defined by the label of the repeater. Figure 2 shows the information carried in the packet header, used for packet transporation.

The handover number is used for flow control and for the HBH ack test as in the broadcast routing algorithm. The "ALL" indicator is used for alternate routing.

When the ALL indicator is non active, the packet is addressed to a single, unique, repeater. The address of that repeater is defined by the hierarchy level indicator and by the label. The hierarchy level indicator is a pointer to the label and defines the number of nonzero fields of the repeater; if these nonzero fields of the repeater match those in the packet label, the packet is addressed to it.

When a repeater exhausts its allowed number of transmissions without receiving a HBH ack, it begins the alternate routing stage. Alternate routing is initiated by activating the ALL indicator in the packet*. This addresses the packet to all repeaters which match the Hierarchy Level Indicator. When a repeater is switching a packet received via alternate routing, it attemtps to send the packet back onto the primary route. The objective of the alternate routing is to bypass a repeater which is down or temporary busy. Figure 3 shows, schematically, the packet flow when using alternate routing. The

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* Other schemes for alternate routing are presented in Section 3.5.

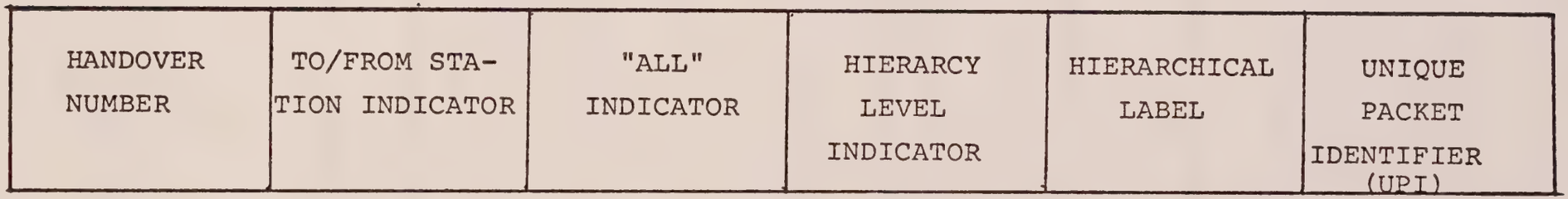


FIGURE 2: HEADER SECTION FOR PACKET TRANSPORTATION USING HIERARCHICAL ROUTING

example shows alternate paths available to repeater A for sending the packet to repeater C, when encountering blocking on the primary path. All the alternate paths are used simultaneously.

The processing performed by a repeater upon packet reception is as follows(the test for determining a HBH ack is not specified):

1. If packet is received in error, discard packet; go to (8),

2. If repeater's hierarchy level does not match that in the packet go to (8),

3. If the nonzero fields of repeater label match those in the packet go to (5)

4. If ALL indicator is not active, discard packet; go to (8),

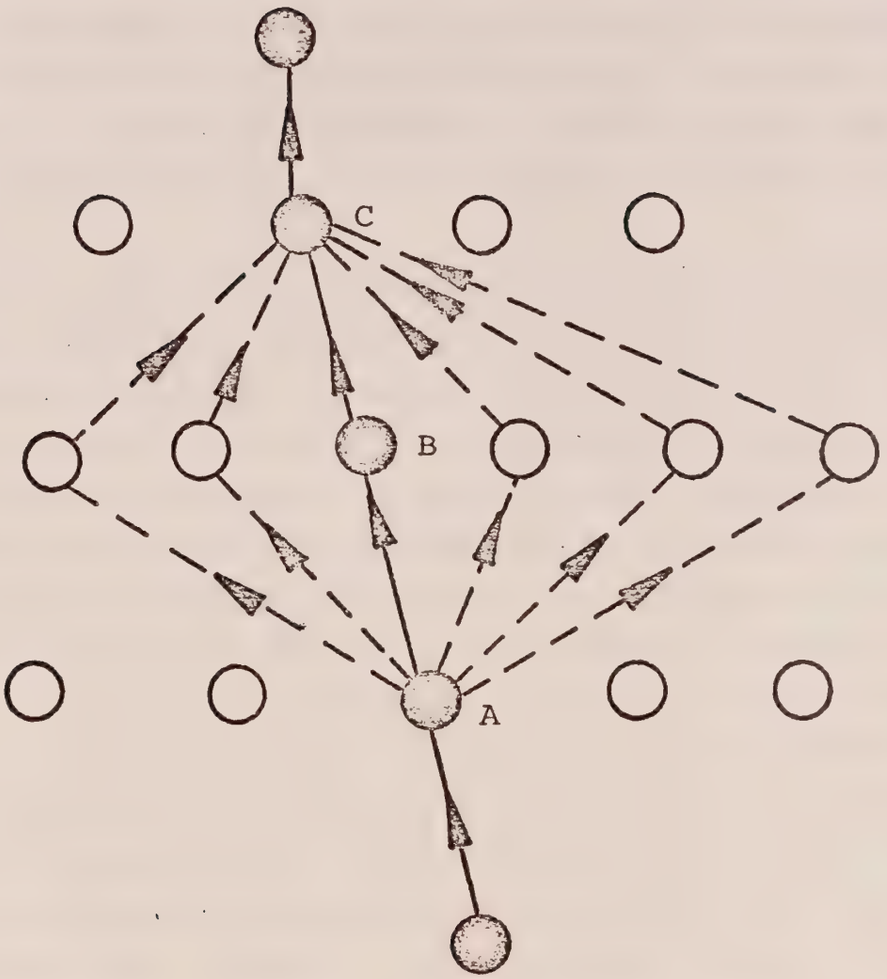
5. Deactivate ALL indicator,

6. (a) decrement handover number
   (b) if packet is TO station, decrement hierarchy level indicator
   (c) if packet is FROM station, increment hierarchy level indicator.

7. Initialize packet for transmission,

8. End.

The only step required for addressing the next repeater on the assigned path is changing the hierarchy level indicator in (b) or (c) of Step 6.



SCHEMATIC PRIMARY LINK

SCHEMATIC ALTERNATE LINK

FIGURE 3: ALTERNATE ROUTING EXAMPLE

3.3 Routing in Multi-Station Radio Networks

In a multi-station network, a repeater is assigned a hierarchical label by several stations during the initialization procedure. Upon receiving a new label the repeater determines its Primary Label, Secondary Label, etc; according to its distance in number of hops to the corresponding stations. The above order may be changed as a result of changes in network topology. The primary label can be used for packets without a label (e.g. packets from terminals).

Every repeater can simultaneously route packets to any of the stations to which it is connected, by using essentially, the same algorithm outlined for a single station case. The statioon towards which a packet is routed is essentailly transparent to the repeater. A repeater matches the packet label with one of its labels and then decrements or increments the hierarchy level indicator depending on whether the packet is directed TO or FROM a station. The structure, for routing purposes, formed by the assignment of labels by two stations is shown in the following set of figures. Figures 4 shows connectivity of a network of 48 repeaters and two stations. Figure 5 shows the tree structure generated by the hierarchical labels assigned by Station S-1, and Figure 6 the corresponding tree generated by the labels assigned by Station S-2. Figure 7 shows the two trees overlaid, and the partition of the set of repeaters between the two stations generated by the choice of the primary and secondary labels. All the repeaters above the separation line have a smaller number of hops to S-1 and thus selected the label assigned by S-1 as their primary label; whereas repeaters below the line have chosen S-2 as their primary station. R4, R11, and R18 have the same number of hops to the two stations and their choice is arbitrary.

Station-to-station communication via the radio network, using the hierarchical routing algorithm, is accomplished by the orginating station when acting like a terminal.

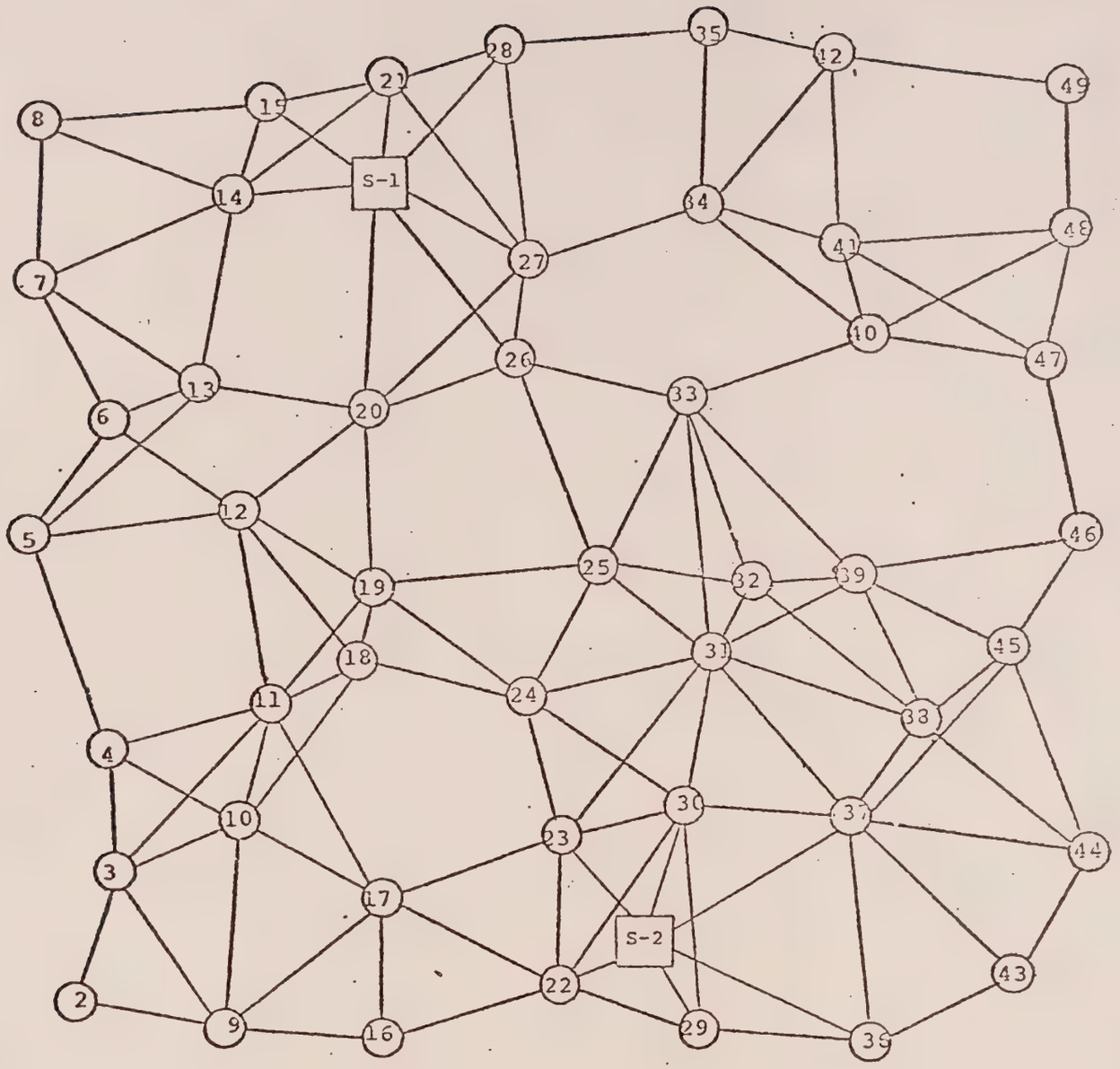


FIGURE 4: CONNECTIVITY OF A RADIO NETWORK WITH TWO STATIONS

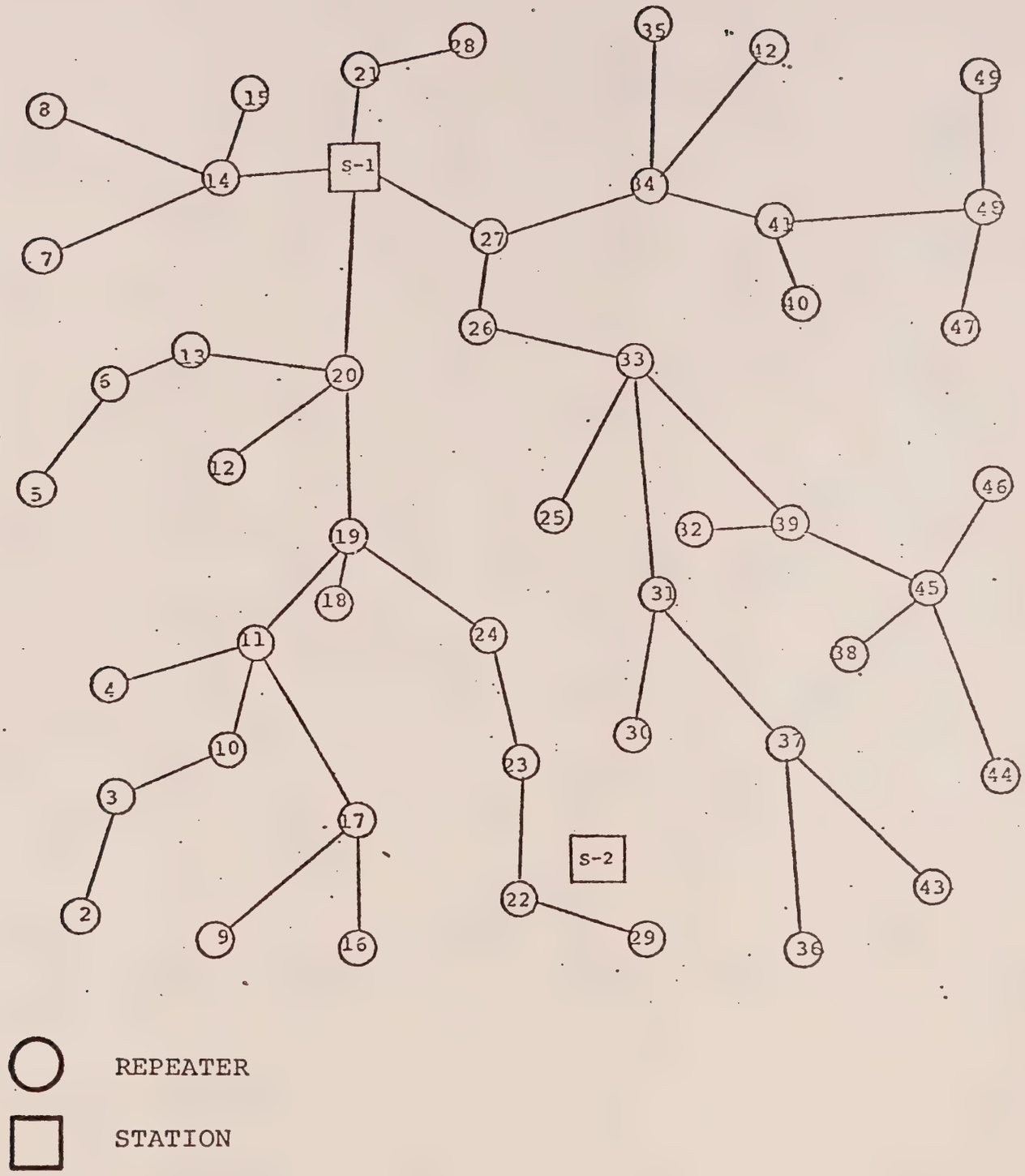


FIGURE 5: TREE STRUCTURE GENERATED BY LABELS ASSIGNED BY STATION S-1

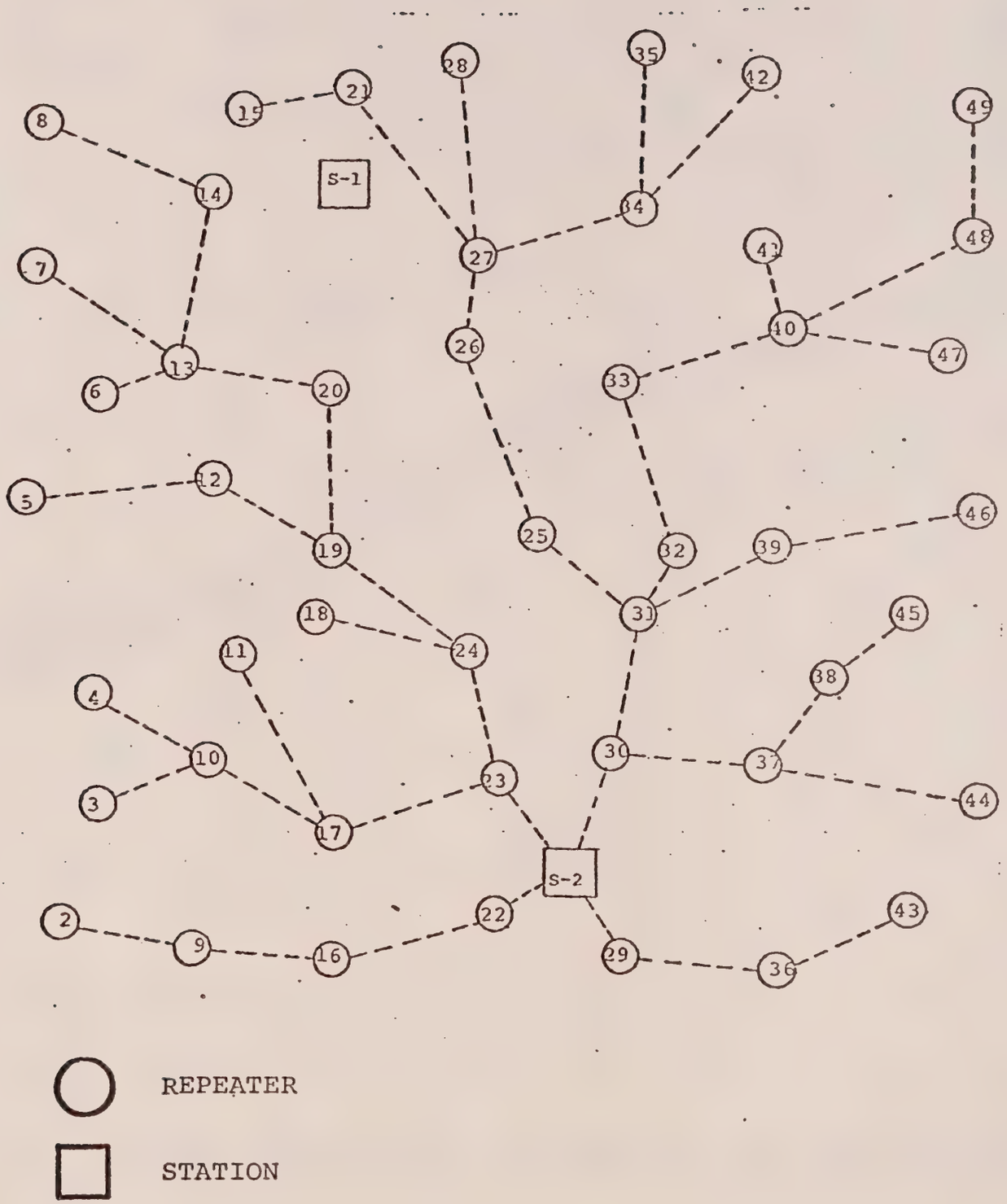


FIGURE 6: TREE STRUCTURE GENERATED BY LABELS ASSIGNED BY STATION S-2

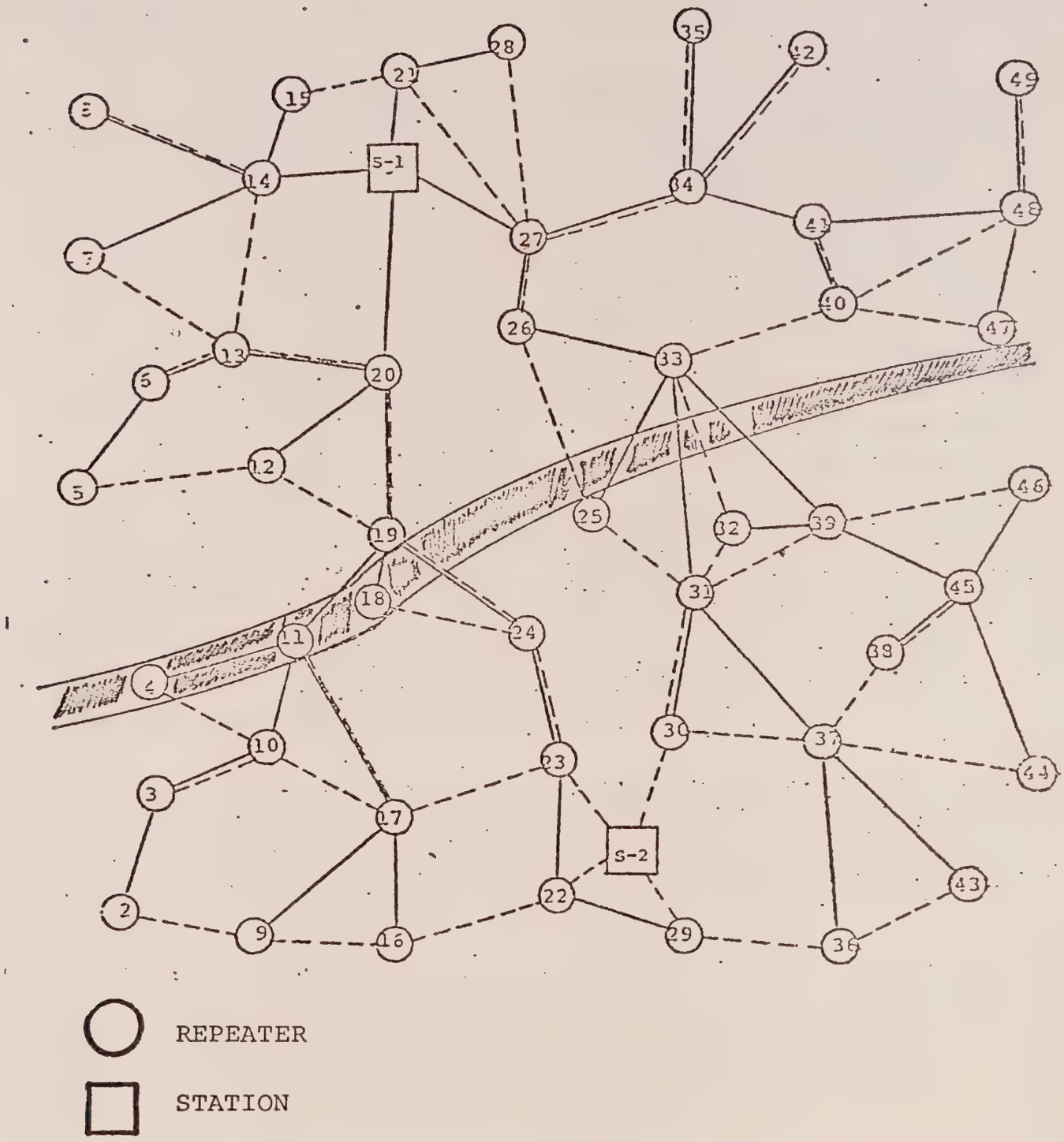


FIGURE 7: PARTITION OF REPEATERS TO PRIMARY AND SECONDARY STATION

3.4 Properties

1. The algorithm performs point-to-point (PTP) routing in the radio network. This enables shortest path routing between repeaters and stations when the labels are properly assigned. The PTP routing results in minimum utilization of processing capacity at nodes, and consequently minimum utilization of the channel capacity due to the small number of nodes which compete for the channel (using a random transmission scheme) when repeating the packet. To clarify the last point, consider a path traversed by a packet using the broadcast and hierarchical routing algorithms, respectively. The delay experienced when using the hierarchical algorithm will, on the average, be much smaller, because only repeaters on the path transmit the packet. This results in a smaller probability of interference and thus a smaller number of transmissions per hop before success, and consequently a smaller delay per hop.

2. There is a high probability that the packet will reach its destination, when taking into account alternate routing. The directionality of the algorithm also implies that the packet will arrive at only one station.

3. The only drawback of the algorithm is the need to maintain an updated set of labels. This, however, becomes a limitation only in a network with highly mobile nodes.

3.5 Discussion

Several possible generalizations of the hierarchical routing algorithm are possible; two of which are now discussed.

Generalization 1: This technique is based on the increase of transmission power when encountering blocking rather than using the "ALL" indicator; and enabling all repeaters on the path which are closer to the destination to accept the packets for switching. Specifically, suppose that repeater R of hierarchy level j+1 transmits a packet towards a station. R addresses the packet to a repeater on the path at hierarchy level j. We now modify the rule to enable all repeaters along the path with a hierarchy level $\leq$ j to receive the packet. The advantage of this technique is that one can shorten the number of hops to the destination and bypass failed repeaters. The limitations are:

1. duplicate copies of the packet are generated,

2. the increase in power results in interference with a larger number of repeaters, and

3. difficulties may be encountered in the HBH ack scheme when the repeater which receives the packet for switching transmits it with a lower power than that used by its predecessor.

Generalization 2: This generalization involves the search for an alternate repeater when encountering blocking. The search protocol involves the transmission of a search packet which specifies the class of repeaters sought and receiving a response from a repeater in that class; the response contains the hierarchical label of the responding repeater. The searching repeater subtitutes the label of the responding repeater into the original packet and transmits the packet.

The essence of this technique is to define the class of repeaters sought. Consider a field from the hierarchical label. We stated two possible codes, a zero or an integer value which identifies a specific repeater. Now, we introduce another code for a field, the "ALL code", which addresses all repeaters in that hierarchy level. Thus, the class of repeaters sought by the search packet can be defined by the specific fields in the label which contain an ALL code. Figure 8 shows the label of a search packet which defines the class of repeaters in hierarchy level 2,3, or 4, associated with the particular station defined by the first field. The class of repeaters sought can be progressively increased as necessary.

The advantage of this technique is that no duplicate copies of the packet are generated along the path. The entire packet is always transmitted to a unique repeater. This technique requires, however, two hierarchical labels in the packet header when routing from the station (towards a repeater); one which may be replaced as a result of the search protocol, and the other which defines the path and enables routing of the packer back onto it after departure. An additional requirement is the search protocol.

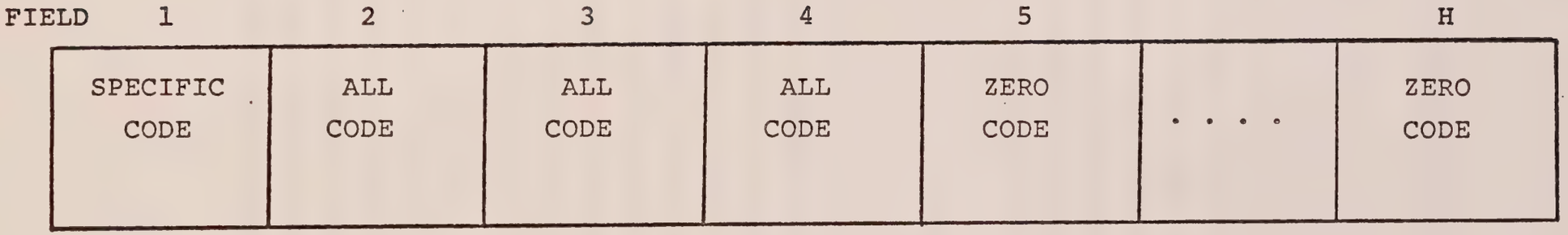


FIGURE 8: THE LABEL OF A SEARCH PACKET WHICH DEFINES A CLASS OF REPEATERS

4. DIRECTED BROADCAST ROUTING ALGORITHM

The development of the hierarchical routing algorithm was based on the assumption that the radio network is used for local collection and distribution of traffic. Furthermore, the stations were assumed to have directories of destinations and accounting capabilities, so that every packet must pass through a station even when destined to a device in the radio network. These assumptions implied a centralized network architecture, and when traffic requirements and reliability considerations were taken into account it resulted in a set of overlayed centralized networks.

We now consider a different set of assumptions. Specifically, suppose that: (1) the traffic requirements are uniform; that is, it is equally likely to have the same traffic requirement between any pair of nodes (repeaters and stations) in the network; (2) that the traffic origination device knows (or can obtain) the ID of the destination repeater, and (3) that accounting per packet or per message is not needed. These assumptions imply a distributed network architecture. The concept is applicable to cases in which most of the resources are on the radio network. It is characteristic of cases in which the network resources and users belong to the same entity, such as in military applications. The hierarchical routing can still be used; however, a distributed routing approach in which a packet is routed directly to the destination repeater may be more appropriate, and is presented in this section.

It is still assumed that the capabilities of repeaters are limited and that stations will perform all the tasks not directly related to packet switching, as well as acting as repeaters. The

main task of a station in a distributed radio network is as an observer and controller. Specifically, the station will perform the following:

1. Network initialization; this is the same function needed when using hierarchical routing. The station maps the network topology, determines labels to be assigned to repeaters and initializes repeaters.

2. Monitoring network connectivity and changing repeaters labels as necessary.

3. Global flow control functions and controlling operating parameters of repeaters.

4. Gateway: all traffic to destinations not in the radio network, must go through a station.

5. Supervisor: Extra capabilities needed by a terminal or by a repeater will be requested from a station. For example, the directory of resources which changed locations.

4.1 The Repeater Label

The label contains similar information to that available to IMPs in the ARPANET [FULTZ,1971; GERLA,1973]. In the ARPANET, node i has a table A of (N-1) xL_i entries, where N is the number of nodes in the network and L_i is the number of outgoing point-to-point channels (links) from node i. An entry a_{kj} indicates the distance (or delay) from node i to node k when using outgoing link j.

The notion of point-to-point link in meaningless in broadcast radio networks. A repeater is assigned a label in the form of a distance vector. Repeater i, R_i, will be given the vector $\underline{di}$ = (dij), where dij is the minimum number of hops from R_i to R_j. We propose a convention that stations will be numbered from 1 to S, where S is the number of stations, and repeaters from S+1 on; so that if a repeater requires extra capabilities from a station, it can select an arbitrary number from 1 to S, as its destination; providing the distance to it is finite.

If we assume that there are N nodes in the network (repeaters and stations), the maximum distance is N-1 hops, and it is needed to represent a distance of ∞*. Thus one needs a total of $N\log_2 N$ bits for storing the vector $\underline{di}$.

Note that Ri is not provided with the IDs of its neighbors; in fact, its own ID (R_i) is not explicitly known to it; the latter is implicitly given by the fact that $d_{ii}=0$.

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* The distance of ∞ can be used by a station to prevent communication between a repeater and a set of repeaters, for partitioning the repeater network among the stations, or possibly for turning a repeater off, when all entries apart from dii are ∞.

4.2 The Routing Algorithm

Figure 9 shows the information carried in the packet header for use by the directed broadcast algorithm. The handover number is used for flow control to limit the number of hops that a packet traverses. The destination ID and the distance to it from the transmitting device are used for the HBH ack and for determining the devices that need to accept the packet for switching.

Essentially, the rule for accepting a packet for switching is that the receiving device is closer to the destination than the transmitting device. The destination device identifies that a packet is for it by noticing that its distance to the destination is zero. We now outline the processing done by a repeater along the path.

Suppose that Rk transmits a packet which is destined to Ri; the entries in the header section of Figure 9 are therefore Ri and dki. The processing done by Rj, $j \neq k,i$, upon receiving the packet is:

1. If packet is received in error, discard packet, go to (7),

2. If packet is a HBH ack, discard packet received and packet acknowledged; go to (7),

3. If handover number equals zero, discard packet received, go to (7),

4. If dji $\geq$ dki, discard packet received, go to (7),

5. (a) decrement handover number
   (b) set dji into packet header

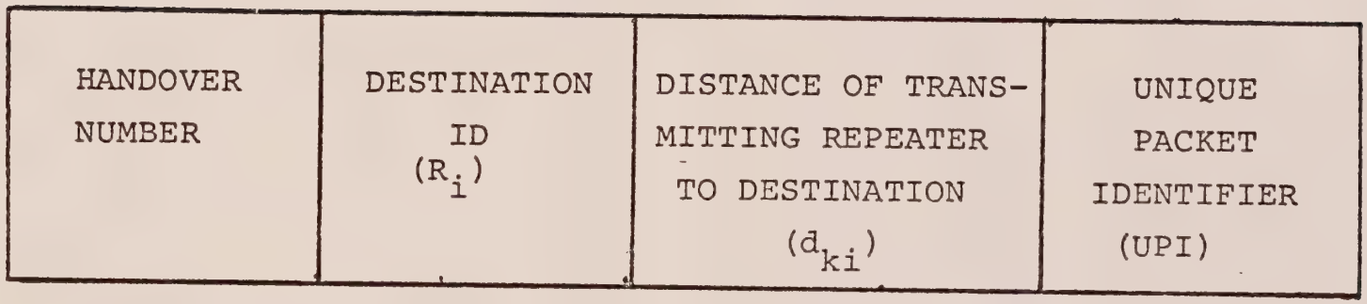

FIGURE 9: HEADER SECTION FOR PACKET TRANSPORTATION USING DIRECTED BROADCAST ROUTING

6. Initialize packet for transmission,

7. End.

In Step 2, the received packet is a HBH ack to a stored packet if it has the same UPI and if dji > dki. The only change in the header needed for routing is the substitution of dji into the packet header.

When encountering blocking, a repeater may increase its transmission power, thus increasing the number of potential receivers. This, however, may result in some difficulties in obtaining a HBH ack, as discussed in Section 3.5. As a last option, the repeater may send a control packet to a station to resolve the difficulty.

4.3 Properties

1. The algorithm enables direct (i.e. not via a station) routing to any repeater or station in the radio network.

2. There is a high probability of reaching the destination node. In fact, if we ignore traffic overload, if there is a path to the destination, the packet will "find" it. The packet is routed to a single destination.

3. It is claimed that the algorithm has the property of shortest path routing. This is due to the HBH ack scheme used, which eliminates repeaters on the basis of distance to the destination, rather than the number of hops that the packet traversed.

4. The algorithm does not have the property of point-to-point routing. It enables the generation of copies of the packet along the path. This implies that its efficiency, in terms of processing capacity at nodes and channel utilization will be less than that of the hierarchical routing algorithm, for repeaters to stations paths.

5. The main limitation of the algorithm is in the need of maintaining an updated set of labels. The algorithm, in the form presented, is suitable for stationary network nodes. That is, when the local connectivity of a single device is changed, it affects the labels of other devices in the network. In this case it may not be efficient to have the stations initialize repeaters and monitor network connectivity. If the application implies a distributed architecture and the network elements (repeaters and stations) are mobile, the task of updating distance vectors should be distributed. This will require more capabilities of the repeaters.

5. CONCLUDING REMARKS

Three routing algorithms for broadcast radio networks were proposed in this paper. The algorithms take advantage of the properties of radio networks in minimizing the utilization of network resources for packet transportation.

The broadcast routing algorithm is the least efficient; however, devices need not be initialized beforehand. The comparison between the hierarchical routing algorithm and the directed broadcast algorithm is not obvious. The directed broadcast algorithm seems to be better from the reliability point of view because of the feature of being a non point-to-point algorithm in which more than one receiver may accept the packet for switching. The reliability is further enhanced if an adaptive power mechanism is available in repeaters. Note also that the efficient HBH ack scheme should cancel out many of the possible paths, in particular when the packet approaches the destination. However, given a path between a repeater and a station, it is apparent that the directed broadcast algorithm will utilize more network resources than the hierarchical routing algorithm.

Another point for comparison, which may become major, is the flexibility of expanding the network and the overhead of updating repeater lables. In this regard the hierarchical routing algorithm is preferable to the directed broadcast algorithm. When a new repeater is added, it is necessary to change all the labels of existing repeaters in the directed broadcast technique; whereas when using the hierarchical algorithm it is only necessary to initialize the new repeater. Furthermore, the fact that all packets are routed via a station, in the hierarchical algorithm, enables easy monitoring

of network connectivity (by the stations) and faster updating of labels.

An analytic comparison of the algorithms is rather difficult. The broadcast and hierarchical algorithms were simulated and extensively tested, some results appear in [FRANK;1975]; the directed broadcast algorithm has not yet been experimentally evaluated.

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